Neuroscientist 2017 vol.23 N5, pages 441-453

Feed-Forwardness of Spinal Networks in Posture and Locomotion

Gerasimenko Y., Sayenko D., Gad P., Liu C., Tillakaratne N., Roy R., Kozlovskaya I., Edgerton V.
Kazan Federal University, 420008, Kremlevskaya 18, Kazan, Russia

Abstract

© SAGE Publications. We present a new perspective on the concept of feed-forward compared to feedback mechanisms for motor control. We propose that conceptually all sensory information in real time provided to the brain and spinal cord can be viewed as a feed-forward phenomenon. We also propose that the spinal cord continually adapts to a broad array of ongoing sensory information that is used to adjust the probability of making timely and predictable decisions of selected networks that will execute a given response. One interpretation of the term feedback historically entails responses with short delays. We propose that feed-forward mechanisms, however, range in timeframes of milliseconds to an evolutionary perspective, that is, "evolutionary learning." Continuously adapting events enable a high level of automaticity within the sensorimotor networks that mediate "planned" motor tasks. We emphasize that either a very small or a very large proportion of motor responses can be under some level of conscious vs automatic control. Furthermore, we make a case that a major component of automaticity of the neural control of movement in vertebrates is located within spinal cord networks. Even without brain input, the spinal cord routinely uses feed-forward processing of sensory information, particularly proprioceptive and cutaneous, to continuously make fundamental decisions that d efine motor responses. In effect, these spinal networks may be largely responsible for executing coordinated sensorimotor tasks, even those under normal "conscious" control.

http://dx.doi.org/10.1177/1073858416683681

Keywords

central pattern generation, feed-forward control, spinal automaticity, spinal cord injury, spinal learning

References

[1] Angeli CA, Edgerton VR, Gerasimenko YP, Harkema SJ,. 2014. Altering spinal cord excitability enables voluntary movements after chronic complete paralysis in humans. Brain 137 (Pt 5): 1394-409.

[2] Belen'kii VE, Gurfinkel VS, Pal'tsev EI,. 1967. Control elements of voluntary movements. Biofizika 12 (1): 135-41.

[3] Bodine SC, Roy RR, Eldred E, Edgerton VR,. 1987. Maximal force as a function of anatomical features of motor units in the cat tibialis anterior. J Neurophysiol 57 (6): 1730-45.

[4] Bouisset S, Zattara M., 1987. Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J Biomech 20 (8): 735-42.

[5] Capaday C, Stein RB,. 1986. Amplitude-modulation of the soleus H-reflex in the human during walking and standing. J Neurosci 6 (5): 1308-13.

[6] Capaday C, Stein RB,. 1987. Difference in the amplitude of the human soleus H reflex during walking and running. J Physiol (Lond) 392: 513-22.

[7] Cordo PJ, Nashner LM,. 1982. Properties of postural adjustments associated with rapid arm movements. J Neurophysiol 47 (2): 287-302.

[8] Courtine G, Gerasimenko Y, van den Brand R, Yew A, Musienko P, Zhong H, and others. 2009. Transformation of nonfunctional spinal circuits into functional states after the loss of brain input. Nat Neurosci 12 (10): 1333-42.

[9] Crenna P, Frigo C., 1987. Excitability of the soleus H-reflex arc during walking and stepping in man. Exp Brain Res 66 (1): 49-60.

[10] Duysens J, Clarac F, Cruse H., 2000. Load-regulating mechanisms in gait and posture: comparative aspects. Physiol Rev 80 (1): 83-133.

[11] Dyhre-Poulsen P, Simonsen EB, Voigt M., 1991. Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man. J Physiol 437: 287-304.

[12] Edamura M, Yang JF, Stein RB,. 1991. Factors that determine the magnitude and time course of human H-reflexes in locomotion. J Neurosci 11 (2): 420-7.

[13] Edgerton R, Grillner S, Sjostrom A, Zangger P., 1976. Central generation of locomotion in vertebrates. In: Stein PS, Stuart DG, editors. Neural control of locomotion. New York: Plenum. p. 439-64.

[14] Edgerton VR, Leon RD, Harkema SJ, Hodgson JA, London N, Reinkensmeyer DJ, and others. 2001 a. Retraining the injured spinal cord. J Physiol 533 (Pt 1): 15-22.

[15] Edgerton VR, Roy RR, de Leon RD,. 2001 b. Neural Darwinism in the mammalian spinal cord. In: Patterson MM, Grau JW, editors. Spinal cord plasticity: alterations in reflex function. Berlin: Springer. p. 185-206.

[16] Field-Fote EC, Dietz V., 2007. Single joint perturbation during gait: preserved compensatory response pattern in spinal cord injured subjects. Clin Neurophysiol 118 (7): 1607-16.

[17] Forssberg H, Grillner S, Rossignol S., 1975. Phase dependent reflex reversal during walking in chronic spinal cats. Brain Res 85 (1): 103-7.

[18] Forssberg H, Grillner S, Rossignol S., 1977. Phasic gain control of reflexes from the dorsum of the paw during spinal locomotion. Brain Res 132 (1): 121-39.

[19] Gerasimenko YP, Ichiyama RM, Lavrov IA, Courtine G, Cai L, Zhong H, and others. 2007. Epidural spinal cord stimulation plus quipazine administration enable stepping in complete spinal adult rats. J Neurophysiol 98 (5): 2525-36.

[20] Gordon KE, Wu M, Kahn JH, Schmit BD,. 2010. Feedback and feedforward locomotor adaptations to ankle-foot load in people with incomplete spinal cord injury. J Neurophysiol 104 (3): 1325-38.

[21] Grillner S,. 1979. Interaction between central and peripheral mechanisms in the control of locomotion. Prog Brain Res 50: 227-35.

[22] Harkema S, Gerasimenko Y, Hodes J, Burdick J, Angeli C, Chen Y, and others. 2011. Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia: a case study. Lancet 377 (9781): 1938-47.

[23] Harkema SJ, Hurley SL, Patel UK, Requejo PS, Dobkin BH, Edgerton VR,. 1997. Human lumbosacral spinal cord interprets loading during stepping. J Neurophysiol 77 (2): 797-811.

[24] Heng C, de Leon RD,. 2007. The rodent lumbar spinal cord learns to correct errors in hindlimb coordination caused by viscous force perturbations during stepping. J Neurosci 27 (32): 8558-62.

[25] Hofstoetter US, Danner SM, Freundl B, Binder H, Mayr W, Rattay F, and others. 2015. Periodic modulation of repetitively elicited monosynaptic reflexes of the human lumbosacral spinal cord. J Neurophysiol 114 (1): 400-10.

[26] Ichiyama RM, Courtine G, Gerasimenko YP, Yang GJ, van den Brand R, Lavrov IA, and others. 2008. Step training reinforces specific spinal locomotor circuitry in adult spinal rats. J Neurosci 28 (29): 7370-5.

[27] Kuo AD,. 2002. The relative roles of feedforward and feedback in the control of rhythmic movements. Motor Control 6 (2): 129-45.

[28] Lacquaniti F, Maioli C., 1989. The role of preparation in tuning anticipatory and reflex responses during catching. J Neurosci 9 (1): 134-48.

[29] Lam T, Anderschitz M, Dietz V., 2006. Contribution of feedback and feedforward strategies to locomotor adaptations. J Neurophysiol 95 (2): 766-73.

[30] Lavrov I, Courtine G, Dy CJ, van den Brand R, Fong AJ, Gerasimenko Y, and others. 2008. Facilitation of stepping with epidural stimulation in spinal rats: role of sensory input. J Neurosci 28 (31): 7774-80.

[31] Layne CS, Mulavara AP, McDonald PV, Pruett CJ, Kozlovskaya IB, Bloomberg JJ,. 2001. Effect of long-duration spaceflight on postural control during self-generated perturbations. J Appl Physiol (1985) 90 (3): 997-1006.

[32] Layne CS, Spooner BS,. 1990. EMG analysis of human postural responses during parabolic flight microgravity episodes. Aviat Space Environ Med 61 (11): 994-8.

[33] Lyon IN, Day BL,. 1997. Control of frontal plane body motion in human stepping. Exp Brain Res 115 (2): 345-56.

[34] Manoonpong P, Parlitz U, Worgotter F., 2013. Neural control and adaptive neural forward models for insect-like, energy-efficient, and adaptable locomotion of walking machines. Front Neural Circuits 7: 12.

[35] Massion J,. 1992. Movement, posture and equilibrium: interaction and coordination. Prog Neurobiol 38 (1): 35-56.

[36] Musienko P, Courtine G, Tibbs JE, Kilimnik V, Savochin A, Garfinkel A, and others. 2012. Somatosensory control of balance during locomotion in decerebrated cat. J Neurophysiol 107 (8): 2072-82.

[37] Musienko PE, Gorskii OV, Kilimnik VA, Kozlovskaya IB, Courtine G, Edgerton VR, and others. 2015. Regulation of posture and locomotion in decerebrate and spinal animals. Neurosci Behav Physiol 45 (2): 229-37.

[38] Parker D, Grillner S., 1999. Activity-dependent metaplasticity of inhibitory and excitatory synaptic transmission in the lamprey spinal cord locomotor network. J Neurosci 19 (5): 1647-56.

[39] Potter SM, El Hady A, Fetz EE,. 2014. Closed-loop neuroscience and neuroengineering. Front Neural Circuits 8: 115.

[40] Shah PK, Gerasimenko Y, Shyu A, Lavrov I, Zhong H, Roy RR, and others. 2012. Variability in step training enhances locomotor recovery after a spinal cord injury. Eur J Neurosci 36 (1): 2054-62.

[41] Shik ML, Orlovsky GN,. 1976. Neurophysiology of locomotor automatism. Physiol Rev 56 (3): 465-501.

[42] Shiratori T, Latash ML,. 2001. Anticipatory postural adjustments during load catching by standing subjects. Clin Neurophysiol 112 (7): 1250-65.

[43] Smith JL, Carlson-Kuhta P, Trank TV,. 1998. Motor patterns for different forms of walking: cues for the locomotor central pattern generator. Ann N Y Acad Sci 860: 452-5.

[44] Timoszyk WK, De Leon RD, London N, Roy RR, Edgerton VR, Reinkensmeyer DJ,. 2002. The rat lumbosacral spinal cord adapts to robotic loading applied during stance. J Neurophysiol 88 (6): 3108-17.

[45] Toussaint HM, Commissaris DA, Beek PJ,. 1997. Anticipatory postural adjustments in the back and leg lift. Med Sci Sports Exerc 29 (9): 1216-24.

[46] Wolpert DM, Miall RC,. 1996. Forward models for physiological motor control. Neural Netw 9 (8): 1265-79.

[47] Ziegler MD, Zhong H, Roy RR, Edgerton VR., 2010. Why variability facilitates spinal learning. J Neurosci. 30 (32): 10720-26.

[48] Zhong H, Roy RR, Nakada KK, Zdunowski S, Khalili N, de Leon RD, and others. 2012. Accommodation of the spinal cat to a tripping perturbation. Front Physiol 3: 112.